DISORDERED BIOPYRIBOLES AND TALC IN CHONDRULES IN THE ALLENDE METEORITE: POSSIBLE ORIGINS AND FORMATION CONDITIONS. Adrian J. Brearley, Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA. e-mail: brearley@unm.edu

It is widely recognized that many of the CV carbonaceous chondrites have experienced aqueous alteration to differing degrees [1-5]. Of the CV chondrites studied to date only Allende shows essentially no evidence of alteration of the fine-grained matrix olivine, consistent with its extremely low bulk water content. However, it has been recognized for some time that phyllosilicate phases are present in some components in Allende, especially CAIs [6-8], whereas evidence for alteration of chondrules in Allende is much more limited. A PCP-like phase was reported by [9] in altered opaque nodules in chondrules and rare phlogopite grains occur as a replacement product of mesostasis in <2.5% of 400 chondrules studied by [10]. The presence of phyllosilicates in some CAIs and chondrules in Allende, embedded within an anhydrous matrix, has been widely interpreted as the result of preaccretionary aqueous alteration [2,7,8]. However, based on observations of dark inclusions in Allende, it has been argued that many of the textural and mineralogical characteristics of Allende may be the result of aqueous alteration, followed by a period of thermal metamorphism [11-13]. This model suffers from the lack of compelling evidence for the widespread presence of phyllosilicate phases in chondrules in Allende. However, in this study I present TEM observations of pyroxene-rich chondrules in Allende which provide strong evidence that aqueous alteration has affected a much wider proportion of chondrules than has previously been thought and lends support to the proposed parent body alteration model.

Several pyroxene-rich porphyritic chondrules were selected for study by TEM from a single thin section of Allende. In all the chondrules, the dominant phase is enstatitic pyroxene, with subordinate olivine constituting up to 30 modal% of the chondrule. Low-Ca pyroxene exhibits extensive, but variable alteration to fayalitic olivine, and forsteritic olivines are rimmed and veined by fayalitic olivine, all phenomena which have been described previously [14-17]. The alteration is most advanced in low-Ca pyroxene grains which are on the rim of the chondrules and in contact with either fine-grained matrix or rim olivine. Mesostasis in these chondrules has invariably been altered to a mixture of phases such as nepheline and sodalite. No hydrous phases were observed by SEM. TEM studies show that incipient alteration to hydrous silicate phases is widespread in all the chondrules, but is consistently restricted to the phenocrysts of low-Ca pyroxene. The degree of alteration and the volume of the alteration phases is extremely low, but their development is remarkably widespread within individual enstatite crystals. When imaged with the (100) plane of the enstatite parallel to the electron beam, the most obvious evidence of alteration is the presence of thin, cross-cutting veins, typically ~0.2μm in width, which are filled with fibrous minerals. Analysis of these fibrous phases by selected area electron diffraction (SAED), HRTEM and X-ray microanalysis show that they are consistent with amphibole and talc, the latter being the most abundant. Compositionally, two distinct types of amphibole appear to be present. One has a composition consistent with anthophyllite, whereas the second (less abundant) is a calcic amphibole with a composition close to that of gedrite. The amphibole and talc within the veins have replaced the enstatite topotaxially, such that the (100) planes of both phases are coincident. In addition to the veins, randomly oriented talc and amphibole crystals are also present in contraction cracks within the enstatite [18].These fractures were probably originally filled with Ca-rich primary chondrule glass which has been observed in unaltered chondrule enstatite [18]. In addition to the replacement within contraction cracks and in veins, small, isolated pockets of hydrous phases are also present with the enstatite.

HRTEM imaging of clinoenstatite down the c-axis shows that in regions where incipient alteration to talc has occurred, highly disordered biopyriboles are commonly present. In regions of clinoenstatite showing the least evidence of alteration, isolated double, triple and quadruple chain zippers, that frequently terminate within the pyroxene, are present. As replacement becomes more extensive, wide chain lamellae become more common and random sequences of chains with different widths are observed intergrown with relic clinopyroxene. The regions of disordered biopyriboles can extend for several hundred nanometers parallel to the b axis. However, regions of recognizable ordered biopyriboles are extremely rare, the most typical being lamellae of jimthompsonite 2 to 4 chains wide. In areas where advanced replacement of the clinoenstatite has occurred, lamellae with very

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wide chain widths become very common and the chain width increases as regions of ordered talc are approached. It is clear that this process occurs by the propagation of the wide chain lamellae through regions consisting of disordered biopyriboles with small chain widths (2, 3 and 4). In all cases the talc is crystallographically oriented with its (001) plane parallel to the (100) plane of the enstatite. These observations are essentially identical to the occurrences of terrestrial biopyriboles described by [19,20] and provide strong evidence that the biopyriboles are metastable intermediate phases in the transformation of clinoenstatite to talc. In addition, there is also clear evidence of direct transformation of clinoenstatite to talc as indicated by the presence of pockets of talc with coherent (001) interfaces with clinoenstatite with no evidence of associated biopyriboles.

The relationship of the talc and biopyriboles to the fayalitic olivine which has itself replaced clinoenstatite provides some important constraints on the relative timing of formation of these phases. The veins of talc and biopyriboles which crosscut the clinoenstatite invariably terminate at the interface with fayalitic olivine. They are never observed cutting across regions of fayalitic olivine. Where only partial replacement of the enstatite by fayalitic olivine has occurred, small inclusions of unreacted enstatite, < 0.1 μm in size, may be preserved. In some cases, these inclusions contain isolated double or triple chain zippers, which are obviously terminated at the enstatite-fayalite boundary. These observations strongly indicate that the formation of fayalitic olivine occurred after, or perhaps contemporaneously with, the formation of the talc and biopyriboles.

Implications. The alteration assemblage of talc, amphibole and biopyriboles in Allende chondrules is markedly different from any alteration assemblage which has been observed in other CV chondrites [1-5] or indeed other carbonaceous chondrites in general [21]. The presence of talc and biopyriboles, rather than clay minerals and Fe-rich serpentine, is indicative of higher temperatures of formation and hence a different alteration environment. Although this alteration could have occurred in the nebula, the only compelling evidence to support preaccretionary aqueous alteration is the presence of hydrous phases in some chondrules and CAIs in a given meteorite, associated with similar types of objects which are essentially unaltered. For the case of Allende, there is a growing body of evidence that hydrous phases are more widespread than has previously been thought, particular in CAIs [7,8]. Chondrules have generally been regarded as showing little or no evidence of alteration. However, the observations in this study show conclusively that many chondrules in Allende have also been widely affected by aqueous fluids. Although these observations cannot, as yet, be applied to the full chondrule population, they strongly suggest that aqueous alteration may have affected all the components in Allende and hence is more likely to have occurred after accretion within a parent body.

The textural relationships between talc and fayalitic olivine that replaces enstatite provide some additional constraints on the possible conditions of formation of both phases. The textural observations provide strong evidence that the development of the fayalitic olivine occurred after the hydration reaction which produced the talc and biopyriboles. This indicates that the widely accepted origin for the formation of fayalite by a high temperature nebular process such as condensation is improbable. The formation of fayalitic olivine by such a mechanism requires temperatures of around 1200K [e.g. 22], conditions under which preexisting low temperature phases such as the biopyriboles would not survive. In addition, a nebular scenario for the formation of both fayalitic olivine and hydrous phases would require the hydration reactions to occur at low temperatures followed by a dramatic change in nebular conditions. This is extremely problematical for current nebular models. Thus, either chondrule hydration occurred in the nebula and fayalitic olivine was formed as a result of parent body processes or both events occurred within a parent body.

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